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THE EFFECTS OF HEARING PROTECTORS ON SPEECH COMMUNICATION
AND THE PERCEPTION OF WARNING SIGNALS

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<p>Because hearing protectors attenuate the noise and signal by equal amounts within a given frequency range, reducing both to a level where there is less likelihood of distortion, they often provide improved listening conditions. The crossover level from disadvantage to advantage usually occurs between 80 and 90 dB. However, hearing protectors may adversely affect speech recognition under a variety of conditions. For hearing-impaired listeners, whose average hearing levels at 2000, 3000, and 4000 Hz exceed 30 dB, certain speech sounds will fall below the level of audibility. Visual cues may decrease the disadvantage imposed by hearing protectors. However, the "Occlusion Effect," which decreases vocal output when the talker wears protection, adversely affects the listener's speech recognition. The poorest performance occurs when both talkers and listeners wear protectors.</p> <p>(see reverse side)</p>					
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→ Hearing protectors affect warning signal perception in a similar manner. Again the crossover level seems to be between 80 and 90 dB, and there is greater degradation for individuals with impaired hearing. Earmuffs appear to pose greater problems than plugs, and this is especially true of difficulties in signal localization. Earplugs produce mainly front-back localization errors, while earmuffs produce left-right localization errors as well. Earmuffs also drastically impede localization in the vertical plane.

Special protectors have been developed to enhance speech communication while still providing the necessary attenuation. Non-linear devices can be useful, especially in impulsive noise environments, but they are not always comfortable and practical to use. Earmuffs employing noise cancellation mechanisms or amplification at low and moderate levels show considerable promise.

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June 1989

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THE EFFECTS OF HEARING PROTECTORS ON SPEECH COMMUNICATION AND THE PERCEPTION OF WARNING SIGNALS

I. INTRODUCTION

High levels of noise in the military necessitate the wearing of hearing protection by a large number of personnel in many different environments. It is often necessary to communicate and to hear warning signals while wearing hearing protectors in most of these environments. Traditionally, hearing conservation professionals have informed hearing protector users that these devices will not interfere with the ability to hear speech and warning signals, and in some cases, may even enhance the audibility of desired signals. The response of the users, however, is not always so optimistic. The purpose of this report is to review and analyze the research on this issue so as to gain a more thorough understanding of the effects of hearing protectors on speech and warning signal perception, and to make recommendations for further research where knowledge gaps still exist.

Many reports on the effects of hearing protectors on speech and signal communication are prefaced by descriptions of complaints by users. Surveys and questionnaires indicate that many soldiers and industrial workers dislike hearing protection, for whatever reason. In their study of hearing loss among 3000 Army personnel in the infantry, armor, and artillery branches, Walden and his colleagues found that only 64% of the soldiers sampled said they used hearing protectors, and about 50% of the sample reported that they disliked them (Walden, et al., 1975). Although there can be numerous reasons why users dislike hearing protectors, one of the most common reasons is interference with communication and the perception of warning signals.

A study by the British National Coal Board found, after a one-week trial period of hearing protectors, that 45% of the workers believed that hearing protectors "blocked" or "slightly blocked essential sound" (NCB, 1975, cited in Wilkins and Martin, 1977). Two-thirds of these responses came from personnel who had been wearing earmuffs rather than earplugs. Wilkins and Martin (1982) cite six studies to show that approximately half of the workers who wear hearing protection think they have more difficulty hearing warning sounds with protectors than without them.

There is no doubt that under certain conditions hearing protectors can actually improve the recognition of speech and warning signals in noise. Such improvements tend to occur in noise levels above 80 to 90 dB (Kryter, 1946; Lindeman, 1976; Chung and Gannon, 1979), when only the listeners (not the talkers) are wearing protection (Kryter, 1946), and for listeners with normal hearing (Abel et al., 1982; Rink, 1979; Lindeman, 1976; Chung and Gannon, 1979).

II. THEORETICAL CONSIDERATIONS

The theory behind this improvement in high noise levels is that the protectors attenuate both the noise and the desired signal by equal amounts, thereby reducing the likelihood of auditory distortion, which tends to occur at high listening levels. This distortion has been attributed to a broadening of the auditory filter at high stimulus levels (Wilkins and Martin, 1977;

Coleman et al., 1984), causing proportionately greater disruption by noise masking. The improvement sometimes experienced with hearing protectors may also be due to the non-linear growth of masking, which is especially evident in sound pressure levels above about 80 dB (see Coleman et al., 1984). Because the protectors equally reduce the noise and speech components in a given frequency band, no spectral information should be lost, and the reduction in distortion and masking promotes better listening.

The situation, however, is not always this satisfactory. Most hearing protectors do not attenuate all frequencies equally, but tend to reduce high-frequency sounds considerably more than the low frequencies. Thus, the spectral characteristics of the signal have been changed, giving the low-frequency energy more opportunity to mask the high-frequency components. According to Lazarus (1983), the greater the per-octave attenuation slope of the hearing protector, the greater will be the loss of signal audibility. The audibility of signals may be especially poor when the noise is mostly low and mid-frequency and the signal is higher. Lazarus also reports that changes in the signal's temporal characteristics may occur due to resonance changes beneath the protector and due to non-linear properties of the material (Lazarus, 1983a).

These problems are exacerbated when the hearing protector user is hearing-impaired. In this case, even a protector with relatively flat attenuation simply may reduce the level of the signal to below the listener's hearing threshold level. This condition will, of course, be more likely to occur when the protector's attenuation is significantly greater in the high frequencies, which is often the case. Figure 1, from Lazarus (1983a) shows the effect of a hypothetical earmuff's attenuation on signal audibility with a normal listener (N) and one with a high-frequency sensorineural hearing loss (S). While the protector might actually have enhanced signal detection for the normal listener, it attenuated the signal beneath the hearing-impaired person's hearing threshold levels at nearly all frequencies.

III. EFFECTS OF HEARING PROTECTORS ON SPEECH COMMUNICATION IN NORMAL-HEARING AND HEARING-IMPAIRED LISTENERS

A. Speech Recognition by Normal Listeners

At low and moderate noise levels, hearing protectors impede speech recognition, even with normal-hearing listeners, because they reduce the audibility of important consonant cues. For this reason, the continuous use of hearing protectors during intermittent noise exposure can be a problem. At certain noise levels, however, protectors begin to be advantageous for normal-hearing users, depending on the speech and noise conditions.

In one of the earliest experiments of its kind, Kryter (1946) administered PB words over a public address system in simulated engine-room noise having a negative 5-dB per-octave slope. Subjects wore the V-51R earplugs. The results showed that in background sound pressure levels between 75 and 85 dB, earplugs enhanced speech recognition, and below that level they impeded it. Figure 2 contains a replotting of Kryter's data by Acton (1967), showing the relative advantage and disadvantage between the plugged and open-ear conditions for the 50% word recognition score in the occluded condition. The crossover point appears to be just below 80 dB. This finding is consistent with the 80-dB level cited by Coleman et al. (1984) for the prevention of disruptive effects due to the non-linear growth of masking. In

a masking noise level of 88 dB SPL, Michael (1965) found that earplugs slightly enhanced speech recognition, especially at more favorable speech-to-noise ratios. Approximately the same (88-dB) crossover level was found in a small study by Acton (1967) using monosyllabic words in white noise.

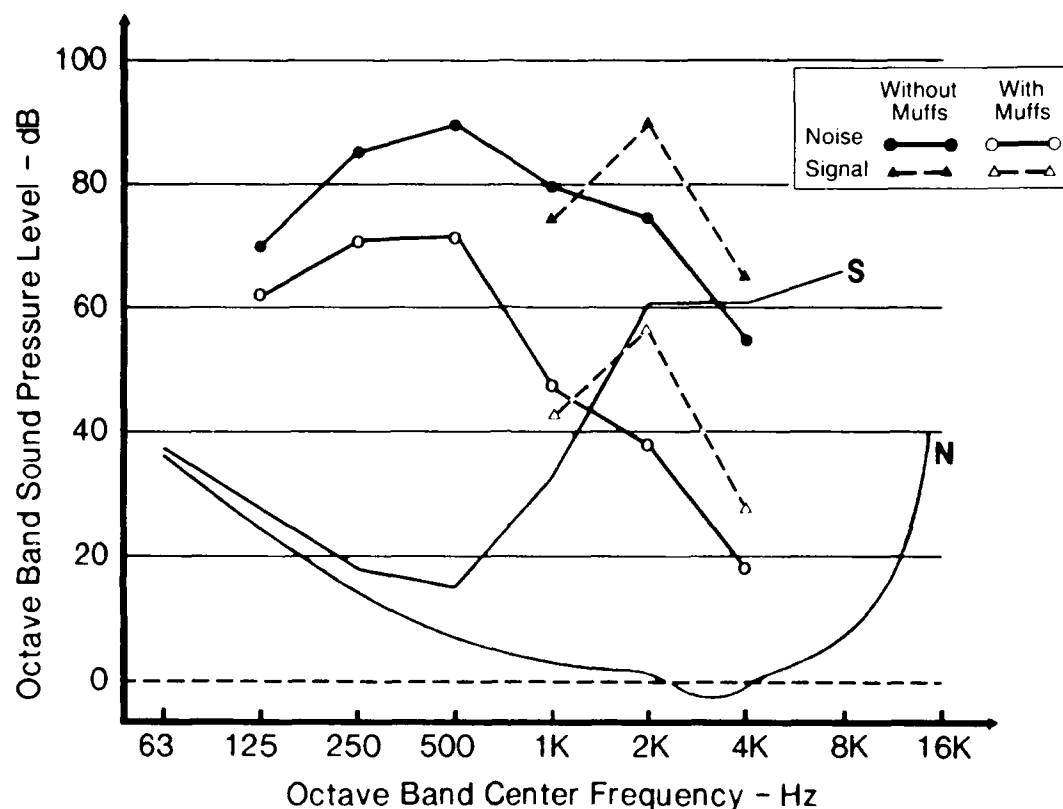


Figure 1. Effect of earmuffs on the audibility of a signal in noise by a subject with normal hearing (N) and one with sensorineural hearing loss (S). Upper curves show octave band levels of signal and noise without muffs, lower curves represent levels with muffs.

Note. From "The Effect of Hearing Protectors on the Perception of Acoustic Signals" by H. Lazarus, 1983, *Zentralblatt für Arbeitsmedizin*, 30, pp. 204-212. Reprinted by permission.

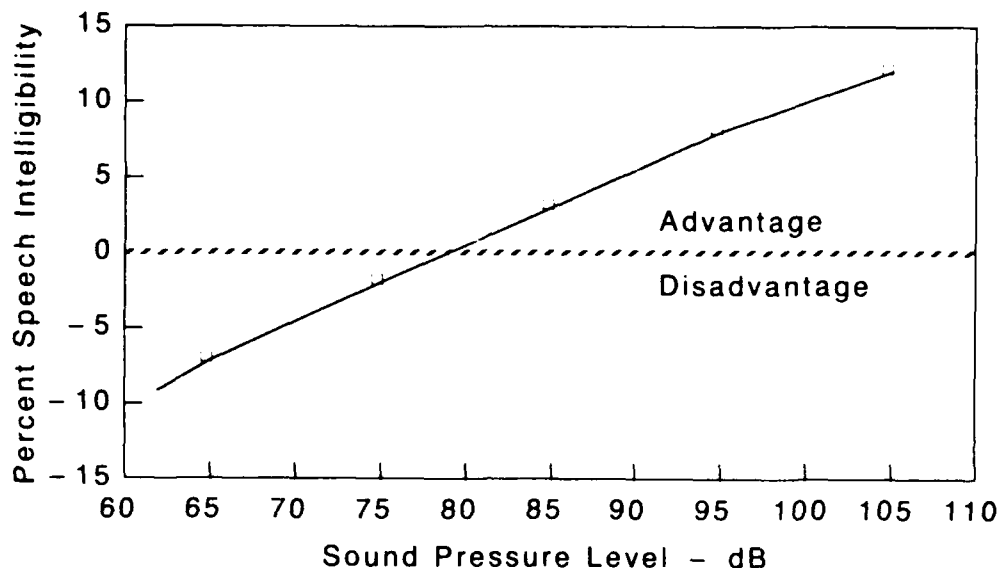


Figure 2. Advantage and disadvantage of wearing earplugs as a function of background sound pressure level. Data points represent occluded speech intelligibility relative to the 50% score in the unoccluded condition. (After Kryter, 1946, and Acton, 1967)

Note. From "Effects of Ear Protective Devices on the Intelligibility of Speech in Noise" by K. D. Kryter, 1946, Journal of Acoustic Society of America, 18, pp. 413-417, and "Effects of Ear Protection on Communication" by W. I. Acton, 1967, Journal of Occupational Hygiene, 10, pp. 423-429. Reprinted by permission.

In a study of hearing protector use with a speech communication system, Pollack (1957) used broadband noise of approximately 70 to 130 dB SPL. Subjects used the V-51R plugs and wax-impregnated cotton. For fixed speech-to-noise ratios, word recognition scores were approximately the same for the protected and unprotected conditions, up to 100 dB at 0 dB speech-to-noise ratio, and up to about 112 dB at +12 dB speech-to-noise ratio, above which levels hearing protectors enhanced performance. With variable speech-to-noise ratios, using an automatic gain control system, earplugs provided even larger improvements at all noise levels tested (100 dB and above).

Other investigations, which have not necessarily intended to identify a specific crossover level, have lent support to the finding that hearing protectors improve speech recognition above certain noise levels for normal-hearing users. For example, a study by Williams *et al.* (1970) showed that normal listeners recognized monosyllables read in a loud voice more

successfully when wearing earplugs than with unoccluded ears. The study involved high levels of aircraft noise (about 116 dB SPL), both in laboratory and field conditions. In another investigation, Howell and Martin (1975) tested speech recognition at various speech-to-noise ratios and found that scores improved with the wearing of earplugs in levels over about 80 to 95 dB.

Lindeman (1976) found that normal-hearing and very slightly impaired listeners also benefited by wearing earmuffs while listening to monosyllables at 90 dB in white noise at 80 dB SPL. Rink (1979) used a 350-2800 Hz band of noise at 90 dB(A) to test the effects of earmuffs on the recognition of speech at 85 dB(A) in quiet (65 dB(A)) and in noise. In quiet, normal listeners performed about the same with and without hearing protectors. In noise, their performance improved with protectors. Chung and Gannon (1979) also report an improvement with earmuffs in noise levels of about 90 dB SPL and a speech-to-noise ratio of +10 dB, but not at a speech-to-noise ratio of -5 dB. They report degraded speech recognition in noise levels of about 65 dB SPL at both speech-to-noise ratios tested (+10 and -5 dB). Abel and her colleagues (1982) found virtually no effect of plugs and muffs on speech recognition by normal listeners in noise levels of 85 dB(A) and speech-to-noise ratios of +5 and -5 dB.

Taken together, these studies point to an enhancement effect above about 80 to 90 dB, which tends to increase both with increasing noise levels and with speech-to-noise ratio. This enhancement appears to be reduced with negative speech-to-noise ratio, and hearing protectors begin to produce an adverse effect in noise levels somewhere below about 80 to 90 dB. There are numerous other factors that lead to a negative effect, and these factors will be explained in the following paragraphs.

B. Speech Recognition by Hearing-Impaired Listeners

Hearing protector users have not always acknowledged the beneficial effects on communication, especially those who have worked in noise environments for long periods of time. One significant reason for dissatisfaction among personnel with many years of noise exposure is probably that they have developed impaired hearing. Over recent decades, researchers have focused their attention on the effects of protectors on users with varying degrees of hearing impairment. For example, Frolich (1970) noted that senior aviators with high-frequency sensori-neural hearing losses did not receive benefits from earmuffs when presented with digits (names of numbers) in noise levels greater than 100 dB.

Many of the investigations mentioned previously in the discussion of speech recognition by normal-hearing users included the effects on hearing-impaired individuals as well. Of Lindeman's 537 Dutch factory workers, most had some amount of noise-induced hearing loss (Lindeman, 1976). The results showed that subjects with fairly good high-frequency hearing (average hearing levels at 2000, 3000, and 4000 Hz no worse than about 25 dB) experienced a slight benefit from wearing earmuffs, but those exceeding an average of about 30 dB performed less well in the protected condition. The greater the hearing loss at these frequencies, the greater was the deterioration of performance.

Rink (1979) compared the performance of 30 hearing-impaired subjects with that of 10 normals, using speech levels of 65 dB(A) in quiet and 85 dB(A) in noise at a speech-to-noise ratio of -5 dB. Unfortunately, the author gives little information on the magnitude of the hearing impairments except that they were at least 30 dB at two or more frequencies from 250 to 8000 Hz. Ten

of the subjects were presbycusic, ten had noise-induced hearing losses, and ten had sensori-neural losses of unknown etiology. In the quiet condition, normal listeners performed equally well with and without earmuffs (as reported above), and the hearing-impaired individuals performed more poorly. In noise, the performance of the normal listeners improved with protectors, and the hearing-impaired listeners performed about the same with and without protectors.

Chung and Gannon (1979) investigated the effects of earmuffs on monosyllable recognition in pink noise delivered at sensation levels of 40 and 65 dB. These levels translated to about 65 and 90 dB SPL, respectively, for normal-hearing subjects, and would have been higher for hearing-impaired subjects according to their speech reception thresholds. The group of 100 subjects included 60 individuals with a history of noise exposure, divided into categories of mild, moderate, or severe high-frequency impairments. Speech-to-noise ratios tested were +10 and -5 dB. The results showed poorer performance with earmuffs for all conditions except for the normal listeners at high sensation levels (about 90 dB). Performance tended to deteriorate with increasing high-frequency hearing loss, which is to be expected, and also in the more favorable speech-to-noise ratio, which is contrary to some of the findings mentioned previously for normal listeners. However, speech recognition scores in the -5 speech-to-noise ratio condition may have been influenced by truncation effects. The authors noticed an interesting difference at the -5 speech-to-noise ratio between response errors in the protected and unprotected modes. With protectors, most of the errors resulted from a failure to respond, whereas in the open condition they were due to an incorrect answer. According to the authors, the former error suggests that hearing protectors often attenuate the signal to inaudible levels, but without protectors the speech signal tends to become distorted by loud noise (or is itself distorted).

In another large study of the effects of hearing protectors on speech recognition, Abel *et al.* (1982) used subjects with mild-to-moderate, flat hearing losses, in addition to subjects with high-frequency (noise-induced) losses and those with normal hearing. The 96 subjects were also divided into fluency categories according to whether or not English was their native language. Subjects listened to monosyllables at 80 or 90 dB(A) in quiet, white noise, or taped "crowd" noise at a constant level of 85 dB(A). Hearing protectors consisted of earmuffs, formable plugs, and premolded plugs. The results showed that although hearing protectors had virtually no effect with normal listeners, those with both kinds of hearing losses performed significantly more poorly with hearing protectors than without them. The difference in word recognition ranged from 10% to 50% depending on the fluency factor and the background noise condition. The non-fluent subjects scored about 10% to 20% lower than the native English speakers, but the effect was independent of protector condition. In addition, subjects scored lower in the simulated crowd noise than in white noise, but this effect was also independent of the open or occluded ear condition. Differences in speech recognition scores among the six protectors were not great, but one of the two muffs tested caused a reduction in scores that was somewhat greater than the other five protectors. Speech recognition by subjects with flat hearing losses was considerably more severely affected by hearing protectors than that of subjects with high-frequency losses.

C. Effects of Visual Cues, Talker's Ear Condition, and Type of Protector

Certain other parameters are also important in the degree to which hearing protectors affect speech recognition. These include the availability of visual cues, whether or not the talker is wearing hearing protection, and the type of protector.

1. Visual Cues

Person-to-person communication can improve speech recognition by the added advantage of visual cues. Rink (1979) found that both hearing-impaired and normal listeners performed better with visual cues, regardless of protector conditions when listening in a noisy background. Martin *et al.* (1976) found an increase of about 30% in high noise levels, due to the introduction of visual cues. The investigators found that visual cues actually decreased the differences between the occluded and unoccluded conditions.

2. Talker's Ear Condition

Another important variable is the ear condition of the talker: whether or not the talker wears protectors. Individuals whose ear canals are occluded by hearing protectors, impacted earwax, or some other cause, will experience the "Occlusion Effect". This means that these individuals hear their voices by bone conduction, and the subjective impression is that their voices sound louder than they do by the normal air conduction route. The natural inclination is to speak more softly.

According to Berger (1986), the magnitude of the occlusion effect (and hence the Lombard Effect), varies according to the fit of the occluding device. Ear protectors that seal the entrance of the canal, such as "semi-aurals" or "canal caps" provide the most occlusion effect, and deeply inserted plugs provide the least. Muffs with a small volume of air under the earcups will produce somewhat more occlusion effect than large-volume muffs. As the occlusion effect increases, it follows that voice level would decrease.

During person-to-person communication in a reverberant room, Kryter (1946) found that hearing protectors produced a decrease of 1 to 2 dB in the talker's voice level. This fact led to slightly lower speech recognition scores on the listener's part. In fact, when both talker and listener wore protection, the crossover point between disadvantage and advantage did not occur until about 105 dB (Kryter, 1946).

Howell and Martin (1975) also investigated the effects of hearing protection on talkers' voice levels and consequent speech recognition by listeners. This time there were no visual cues. They found that when talkers wore earmuffs, voice levels were reduced by an average of 2.7 dB, and with earplugs, the average reduction was 4.2 dB. This reduction occurred in high noise levels (93 dB), but not in quiet (54 dB). In high noise levels, listeners' speech recognition scores improved in the occluded condition. However, they were reduced considerably when the talker wore protection, with average scores falling from 56% to 31%, wiping out the gains that hearing protectors had provided when only the listener had worn protection. The authors said that this reduction was more than would have been expected from the reduction in voice level alone. They suggested that individuals wearing hearing protection may also talk less distinctly, and that their speech may become distorted from hearing their own voices through bone conduction (Howell and Martin, 1975).

In a follow-up investigation, Martin, Howell, and Lower (1976) assessed spectral differences in voice quality between occluded and unoccluded conditions. Their spectral analysis is reproduced in Figure 3, which shows significant differences between speech levels in the open and protected conditions (about 2 to 3 dB(A)), but no significant differences in frequency content. To see if wearing hearing protectors produces subtle changes in voice quality and consequent speech intelligibility decrements, Martin and his colleagues mixed speech recorded by a talker in hearing protectors with noise. They then used speech from unoccluded talkers at the same speech-to-noise ratio, and compared the resulting speech recognition scores. There was no significant difference. Thus, the authors were unable to explain the extreme degradation from the previous experiment (Howell and Martin, 1975).

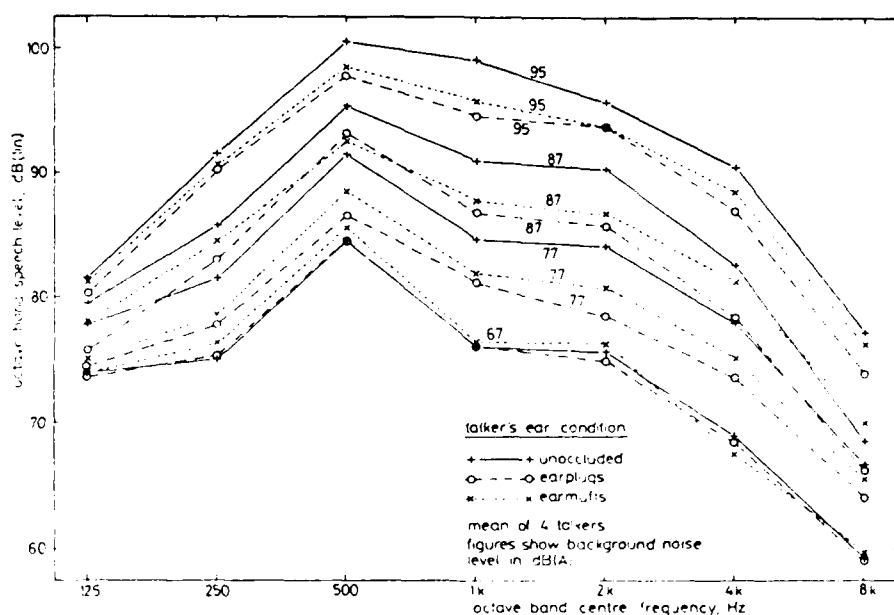


Figure 3. Mean octave band speech levels for levels of background noise from 67 to 95 dB(A). Talkers are unoccluded (+), with plugs (o), or with muffs (x).

Note. From "Hearing Protection and Communication in Noise" by A. M. Martin, K. Howell, and M. C. Lower, 1976, in S. D. G. Stephens (Ed.), Disorders of Auditory Function II, London: Academic Press. Reprinted by permission.

Hoermann et al. (1984) studied the effects of hearing protectors on speech communication in terms of a number of dependent variables, which included speech tempo and speed of communication in addition to speech level and intelligibility. They studied a total of 360 talkers and listeners, unoccluded and using foam earplugs, in pink noise at 76, 84, and 92 dB(A). Speech materials consisted of monosyllabic words, sentences, text from a newspaper, and picture stories (cartoons) which the talker described. Talkers and listeners were separated by a translucent curtain to preclude visual cues. Under certain conditions, listeners provided feedback to the talkers on the extent to which they understood the talkers' communications. The results showed that average speech levels dropped by 4 dB in the 92-dB(A) noise level, which confirms the similar finding of Howell and Martin (1975), but was slightly greater than the 2-3 dB drop found by Martin et al. (1976). The investigators also noted, in the 92-dB(A) condition, that talkers wearing earplugs articulated significantly faster and paused about 25% more briefly between words and phrases. The speed of information exchange, which is a measure of the listener's reaction time, decreased with increasing noise level, and when both talkers and listeners wore protectors.

Speech recognition scores, pooled for all speech materials, are shown in Figure 4, from Hoermann et al. (1984). One can see that earplugs worn by either the talker or listener tended to degrade communication for virtually all of the experimental conditions. Surprisingly, earplugs worn by the listener only failed to improve communication at the highest noise level, although they did improve it somewhat at the 84-dB(A) level. The poorest performance on the speech recognition task occurred when both talkers and listeners wore protectors, which is most characteristic of real-life conditions. The use of feedback, in the form of either verbal communication or a signal light, improved speech recognition scores considerably, as can be seen in Figure 5. When both talker and listener wore earplugs, scores were almost as high as when both were unprotected, at least when the feedback consisted of verbal responses. When the feedback was in the form of a signal light, scores were somewhat lower, but still much improved over the no-feedback condition. Hoermann and his colleagues believe that their experimental conditions are comparable to those found on the job; even the reduced eye contact produced by the translucent curtain, and the 1.5-meter distance between talker and listener. The authors conclude that industrial workers reject ear protectors "...not for some unclear, ill-defined reason, but rather for reasons which can be statistically supported - the impairment of speech intelligibility and deficiency in verbal communication." (p. 77)

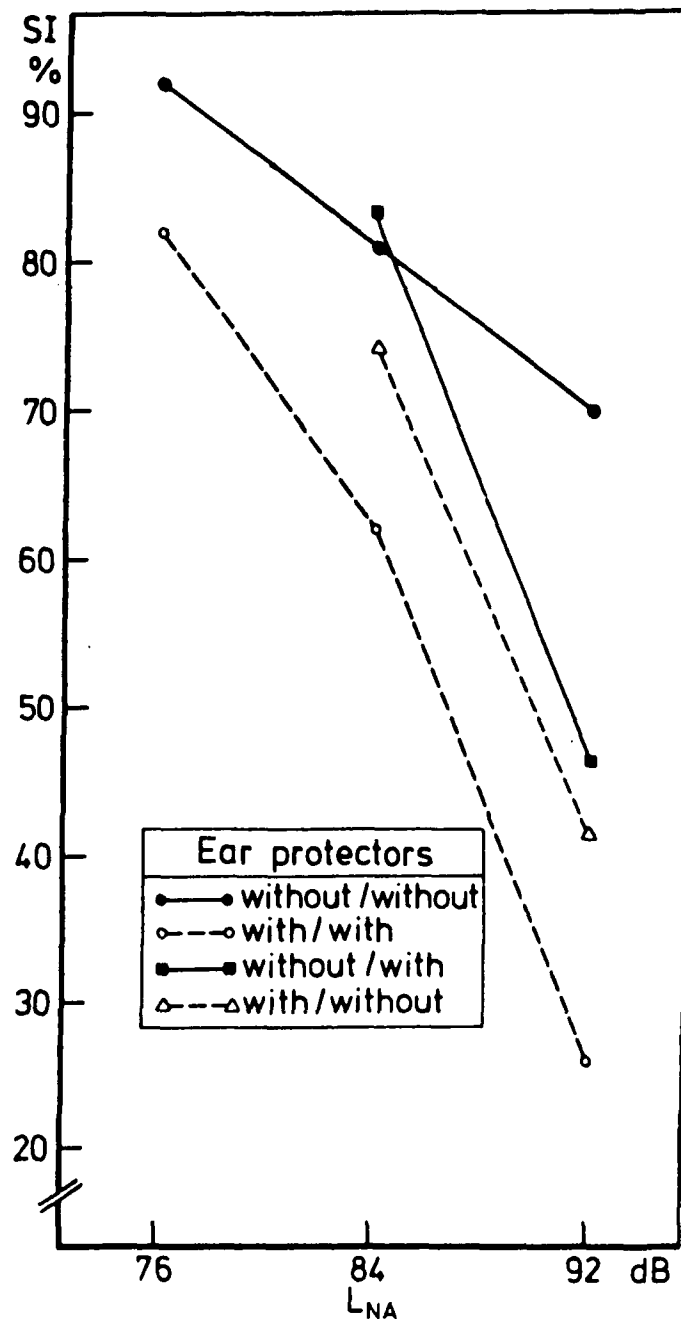


Figure 4. Speech recognition scores (SI) for various kinds of speech stimuli as a function of A-weighted noise level and ear condition (with or without protectors). In the legend, the listing is talker/listener.

Note. From "The Effect of Noise and the Wearing of Ear Protectors on Verbal Communication" by H. Hoermann, G. Lazarus-Mainka, M. Schubeius, and H. Lazarus, 1984, Noise Control Engineering Journal, 23, pp. 69-77. Reprinted by permission.

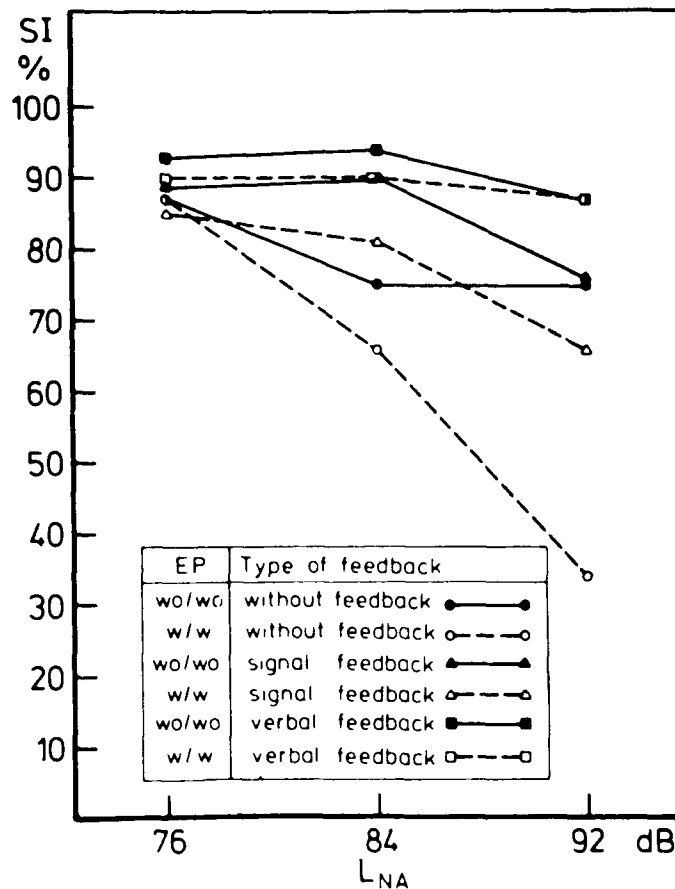


Figure 5. Speech recognition scores (SI) as a function of A-weighted noise level, ear condition (with and without protectors), and three feedback conditions. In the legend, EP = ear protection, and WO/WO = talker without and listener without.

Note. From "The Effect of Noise and the Wearing of Ear Protectors on Verbal Communication" by H. Hoermann, G. Lazarus-Mainka, M. Schubeius, and H. Lazarus, 1984, *Noise Control Engineering Journal*, 23, pp. 69-77. Reprinted by permission.

In an experiment with a somewhat different purpose, Eriksson-Mangold and Erlandsson (1984) investigated the psychological and social effects of "sudden hearing loss" by occluding the ears of normal-hearing individuals. Subjects wore earplugs or material used in making earmolds for 9 1/2 hours, while they engaged in their normal daily activities. The results of a subsequent questionnaire revealed that 28% felt that the distortion of their own voices (by bone conduction) was the factor that most influenced them during the experiment. Interestingly, 57% of the subjects reported considerable inhibition in speaking because they could not control the loudness of their voices. Because the subjects were presented with such categories as "distortion of own voice" and "distortion of laughter, coughing or chewing", the responses were not purely spontaneous. However, a five-point rating scale

allowed the authors to assess the importance of each factor, and it appears that voice distortion and loudness control were significant factors.

3. Type of Protector

Certain investigations have included more than one type of hearing protector, and the results sometimes indicate a difference in effect on speech communication. As mentioned above, Abel *et al.* (1982) used six protectors, consisting of various kinds of plugs and muffs. The results showed that one of the two muffs caused a greater reduction in speech recognition than the other protectors. Howell and Martin (1975) used the V-51R earplug and the Welsh 4530 earmuff. Both protectors gave comparable attenuation in the low frequencies, but the earmuff afforded much greater attenuation at 500 and 1000 Hz and slightly greater attenuation at 2000-6000 Hz than the plug. The investigators found that plugs allowed consistently better speech recognition than muffs, especially in the highest noise condition, which they attribute to the earplug's lower attenuation values in the middle and high frequencies.

IV. EFFECTS OF HEARING PROTECTORS ON WARNING SIGNAL PERCEPTION

A. Signal Detection

The same kinds of theoretical conditions that apply to speech communication with hearing protectors also should apply to the perception of non-verbal stimuli. The principal difference, of course, is that there is likely to be more variation in the acoustical parameters of non-verbal signals. In general, however, one would expect that in high levels of signal and noise, hearing protectors would attenuate both the signal and the noise to more moderate listening levels, thus improving audibility. Evidently, this is what has occurred in a number of experiments.

Levin (1980) used recorded mining noises at levels greater than 90 dB to determine thresholds for pure tones in listeners who wore hearing protectors. He found that for most noises, masked thresholds were the same or lower (better) with hearing protectors than without them, and there was less variability among subjects' scores in the protected condition.

In an elaborate investigation of signal detection in mining noises, Coleman *et al.* (1984) assessed masked threshold for pure tones among 27 mineworkers with varying degrees of hearing loss. Conditions investigated were no protection, circumaural protectors with headband, helmet mounted circumaural protectors, and foam plugs, in noise levels of approximately 90 dB(A). The investigators also tested a method of predicting masked thresholds using a formula based on a modification of critical band theory developed by Patterson *et al.* (1982). The method employed the level and spectrum of the background noise, absolute threshold levels of each subject, estimations of the "filter width" of each subject, and hearing protector attenuation values. The results showed that the use of hearing protectors had no significant effect on mean masked thresholds of audibility for pure tones above 1000 Hz, but they did cause an increase in the range of thresholds above 2000 Hz, especially in listeners with the poorest hearing. Consequently, the investigators recommended the use of warning signals with primary spectral energy in the frequencies below 2000 Hz for the benefits of these listeners. Coleman *et al.* also found a significant increase in masked thresholds for frequencies between 500 and 1000 Hz when subjects wore earmuffs, but not with the foam plugs. Predicted masked thresholds were somewhat higher than actual

thresholds, although the method consistently predicted the general pattern of responses. With minor adjustments, it appears that this prediction method could be used in practical circumstances.

In another study, Forshaw (1977) used broadband noise at 88 dB(A), either with or without line components, to simulate ships' engine and boiler rooms. Three normal-hearing subjects and one with a high-frequency hearing loss attempted to detect six pure tones between 1000 and 6000 Hz. In the continuous-spectrum background noise, normal-hearing subjects performed generally better in the protected condition. In the broadband noise with line components, however, the reverse appeared to be true. The hearing-impaired subject gave about the same performance in the protected and unprotected conditions, except that the 3000-Hz signal was attenuated beneath the threshold of audibility when the subject wore protectors. Although the investigation is severely limited by its small subject population, it suggests that protectors may affect signal detection much the same way they affect speech recognition, enhancing performance in high noise levels with normal listeners, but being a potential source of problems for hearing-impaired listeners.

Wilkins and Martin performed a series of experiments on the effects of hearing protectors on the perception of warning signals by normal-hearing listeners (Wilkins and Martin, 1977, 1981, 1982, 1984, and 1985). In the first of these experiments, (Wilkins and Martin, 1977) 16 subjects listened for a wailing "high-low" siren and a bell at 75 and 95 dB SPL mixed with random noise, with ears unoccluded and while wearing muffs or plugs. Another ear condition was provided by a spectrum-shaper, which was used on the signal-plus-noise mixture to simulate the mean attenuation provided by the earmuffs. The results showed no large effect of ear condition on masked threshold level, although in the 95-dB noise level, the three protected conditions produced lower (better) detection thresholds than the unprotected condition. Detection thresholds were somewhat lower for the bell than for the siren, and this difference appeared to be unrelated to ear condition at the 95-dB level. At the 75-dB level, however, subjects performed slightly better in the unprotected condition, which is not surprising in light of the 80-to-90 dB crossover levels discussed previously. Also, there were only minor differences between performance with the plug and the muff, even though there were considerable spectral differences between them, with the mean attenuation of the muff approximately 20 dB greater than that of the plug at 1000 Hz.

Some investigators report that hearing protectors can degrade the ability to detect warning sounds. Lazarus (1979) tested the effects of wearing earmuffs on the ability of 25 subjects to identify bands of noise at approximately 85 dB(A) with differing spectra. The per-octave slopes of the five noises ranged from -12 to +12 dB. Subjects learned to identify the noises before the test, then listened with and without hearing protection. No competing noise was present. The results showed significantly fewer correct responses with protectors than without.

Subsequent investigations by Wittmann and Lazarus (1980) and Lazarus et al. (1983) (as reported by Lazarus, 1983b) used a signal called a "Typhon" at 76 to 96 dB(A) embedded in noise levels of 80 to 105 dB(A). The Typhon signal is used to warn rail track workers against approaching trains. Subjects included normal-hearing and hearing-impaired listeners using muffs, plugs, and no protectors. The investigators found that normal-hearing subjects performed consistently better with plugs than unprotected by up to 2.5 dB, but consistently worse with muffs, where signal detection threshold levels increased up to 6 dB. Figure 6, from Lazarus (1983b) is based on the data of

Lazarus et al. (1983). It shows the percentage of correctly identified signals as a function of signal level in noise at 97 dB(A), with the parameter being ear condition. One can see that performance is consistently improved by plugs, but degraded by muffs.

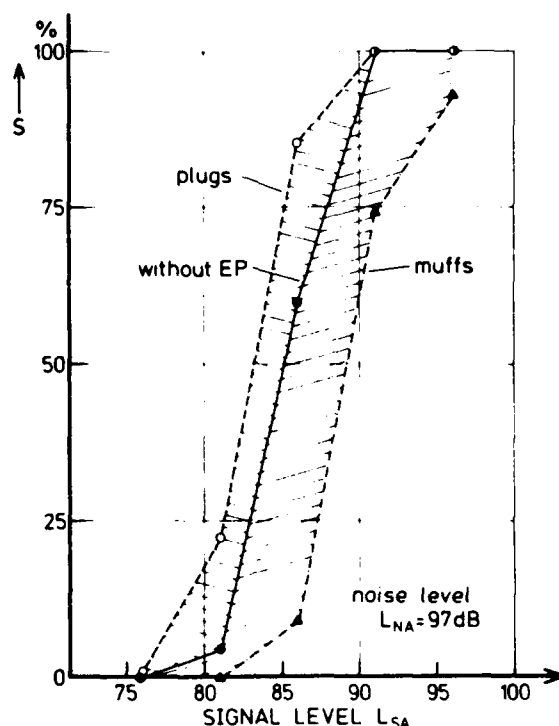


Figure 6. Percentage of correctly identified signals as a function of A-weighted signal level in a noise level of 97 dB(A). The parameter is ear condition: plugs, muffs, or unoccluded.

Note. From Die Wahrnehmbarkeit von Rottenwarntyphonen beim Tragen von Gehörschutz, by H. Lazarus, H. Wittmann, W. Weissenberger, and H. Meissner, 1983, Forschungsbericht Nr. 140 der Bundesanstalt für Arbeitsschutz und Unfallforschung, NW-Verlag Bremerhaven. Reprinted by permission.

Hearing-impaired listeners, tested only with earplugs, performed increasingly poorly as their hearing threshold levels increased, but those with mild impairments performed about as well with earplugs as without them.

B. Detection of Unexpected and Difficult-to-Recognize Signals

Wilkins and Martin (1981) theorized that inattention could elevate the masked thresholds of warning sounds when subjects were not expecting them, and the unexpected condition would be reflective of real-life situations. Consequently, they presented a wailing siren in a background of noise at 75 dB SPL at randomly intermittent intervals. Twelve normal-hearing subjects, with and without earmuffs, listened for the siren while they were engaged in a

tracking task. Subjects received feedback on their performance on the task, and they were also given a monetary incentive for responding to the warning signal. The resulting detection levels were not significantly different from those where the signal was expected, and the addition of earmuffs did not change this finding. The authors do suggest, however, that although the signal was randomly intermittent, there was a "high degree of expectancy" among the subjects. Also the addition of incentives would further tend to minimize any differences.

In their next experiment, Wilkins and Martin (1984) tested the effects of hearing protector use in detecting unexpected signals among irrelevant yet meaningful stimuli. In other words, they combined the factors of attention demand (unexpected signals) and difficult signal recognition. For the background noise the investigators used broadband noise of 75 dB(C), upon which were superimposed four "workshop" sounds: grinder, engine, lathe, and drill noise. For warning sounds, they selected the wailing siren used in previous experiments, and the grinder noise. Sixteen subjects, engaged in a loading task, attempted to detect the warning sounds, which were presented with each of the four workshop sounds (overlaid on the noise background) at five signal-to-noise ratios. While the siren was reliably recognized at all five presentation levels, whether or not it was expected, the grinder was significantly more difficult to recognize when it was unexpected. With respect to the difference between the identification of expected and unexpected signals, the use of hearing protectors had no effect on siren recognition, and a small but non-significant effect on the recognition of the grinder noise.

Wilkins and Martin (1985) then attempted to ascertain whether the difference in warning signal effectiveness between the siren and the grinder could be related to spectral contrast to the background of noise and other signals. They point out that as an intentional alarm sound with a distinct tonality, the siren had a high contrast, both with the irrelevant workshop sounds and with the ambient noise, whereas the grinder had low contrast because of its noise-like character. In this experiment, they chose pure tones at 800, 2000, and 5000 Hz as irrelevant stimuli, superimposed on a background of broadband continuous noise as before. Subjects engaged in a loading task were instructed to identify target sounds consisting of the 2000-Hz tone and a narrow band of noise centered at 2000 Hz. The results indicated that the tone was less effective as a signal than the narrow band of noise, and both sounds were an average of about 6% less well perceived with hearing protectors than without. The authors conclude that the contrast with the irrelevant stimuli was greater for the narrow band of noise than for the tones, and that this factor is important in the recognition of warning sounds. They also conclude that hearing protectors will produce adverse effects in situations where warning sounds are already difficult to perceive, either because of low contrast with environmental noise or because of competing irrelevant stimuli (or both). The addition of 6% failures in perception due to hearing protectors could be of marginal importance or it could be critical, depending on the circumstances. It does, however, argue against overprotection. The authors recommend replicating these studies using hearing-impaired subjects (Wilkins and Martin, 1982).

The experiments cited above by Wilkins and Martin were all conducted in the laboratory. Wilkins (1984), therefore, chose to study the effects of hearing protectors on the perception of warning sounds in the industrial environment. The setting was the press shop of a plant manufacturing air and oil filters for engines. The ambient noise environment was 85 to 95 dB(A), with impulses ranging from 105 to 115 dB(A). Wilkins selected as warning

sounds the horn on a fork-lift truck and the clinking sound of metal pieces spilling out of a container. Three other machinery sounds served as competing irrelevant sounds. They were mixed with pink noise, and, with the signals, were recorded and delivered through loudspeakers. Signals were presented at five sound levels, in an irregular order, and in either a predictable or an unpredictable temporal pattern. Thirty workers performing their regular jobs were instructed to press a button when they heard the target warning sounds. Most subjects had some degree of hearing loss. All wore hearing protection in the afternoon (their own protectors, self-fitted), while most did not in the morning.

The results of Wilkins' study showed that neither target sound was completely effective as a warning signal, as even the highest signal level produced an overall response rate of only 85% (Wilkins, 1984). While subjects with "substantial" hearing losses gave 18% fewer correct responses to the clinking sounds than did those with normal hearing or mild losses, they had no added difficulty hearing the horn. In comparison to the unoccluded condition, the use of hearing protectors produced an average of 9% fewer correct responses to the clinking sound, when the target sounds were unexpected. There were no significant differences in protector conditions when the target sounds were expected, nor were there in either category for the horn signal. The author notes that the decrement caused by hearing protectors (for the clinking sound in the unexpected mode) was greater than that observed in the laboratory, and attributes it to the reduction in loudness, acting in conjunction with the signal's reduced attention demand and the difficulties inherent in recognizing it among competing stimuli. A further explanation might lie in the spectral characteristics of the clinking sound, which the author does not discuss, and the fact that workers' hearing impairments may have interacted more adversely with the clinking sound's spectrum than with the spectrum of the forklift horn.

While Wilkins' study has numerous strengths, it also has some significant weaknesses. As the author points out, the factory conditions "provided a high degree of realism" (Wilkins, 1984, p. 433). The subjects presented a range of hearing threshold levels, they worked at their own jobs, and wore various kinds of hearing protectors, which they fit themselves. The acoustics were those of an actual factory, and the stimuli were appropriate. There were many variables, however, that were partially or totally uncontrolled, which is not surprising in such circumstances. For ethical reasons, the investigator could not demand that all workers participate without protectors during certain portions of the experiment, so some workers wore protectors during the "unoccluded" periods. This would tend to reduce differences, so one could possibly expect a greater decrement due to protectors in reality. In addition, there were large variations in noise levels caused by the actual machinery, which would produce uncontrolled variations in the signal-to-noise ratios of the experimental conditions. There was also a variety of actual "irrelevant" stimuli, such as occasional real horns, and the possibility that subjects responded by observing the responses of other subjects. Thus, the results of this study should be interpreted with great caution. Nonetheless, it is the only one of its kind, it generally supports the findings of the laboratory studies that preceded it, and it should provide added incentive for the careful selection of warning signals and against the practice of over-protection.

C. Effects of Hearing Protectors on Localization

Industrial workers have complained that hearing protectors, and in particular, earmuffs, reduce the ability to determine the direction of a sound source. W.G. Noble and his colleagues have investigated this problem in a series of laboratory experiments (Atherly and Noble, 1970; Noble and Russell, 1972; Russell and Noble, 1976; and Noble, 1981).

In the first experiment, Atherly and Noble (1970) tested the effects of earmuffs on the ability to localize a 1000-Hz pure tone in the horizontal plane. Subjects were 15 men who had been working in a foundry, and consequently had some degree of hearing loss. None had used hearing protectors before. Subjects' heads were not restrained, but they were instructed not to move. The 1000-Hz tones were presented at four sensation levels from six loudspeakers, arranged in a circle surrounding the subject. Analysis of the responses showed that the use of earmuffs significantly increased the number of contralateral (left-right) localization errors, from 13 unoccluded to 113 occluded for the group as a whole. The number of ipsilateral (front-back) errors increased, but was not significantly greater, with hearing protectors. However, the distribution of errors changed, with significantly more rearward than frontward errors. Because of a relatively low correlation between hearing threshold level and total errors, the investigators believed that hearing sensitivity was not an important factor. They concluded that "...ear-defenders need to be viewed with suspicion from the point of view of safety in industry" (Atherly and Noble, 1970, p. 265).

In an attempt to explain the effects found by Atherly and Noble, Noble and Russell (1972) tested two hypotheses. First, they theorized that the metal headband connecting the muffs might act as a conducting pathway, and interfere with the two ears' proper analysis of phase and intensity information. To test this hypothesis they modified the earmuffs by removing the headband and instructing subjects to hold the muffs against their ears. The second hypothesis was that the attenuation of earmuffs (or any protector) causes disruption of normal auditory contact with the environment by the attenuation of extraneous sound. To test this hypothesis, the authors used earplugs in addition to muffs. Fifteen normal-hearing subjects listened for a 1000-Hz pure tone and a band of white noise, both at a sensation level of 20 dB. Loudspeakers were arranged horizontally in a circle, as before.

The results of testing the first hypothesis again showed a significant increase in left-right errors, and this time front-rear errors as well, with the wearing of earmuffs. The muffs produced a greater decrement for the white noise than for the tone. There was no significant difference in the number of errors resulting from the modified or unmodified muffs and hence the first hypothesis was rejected. Testing the second hypothesis resulted in significantly better performance with plugs than with muffs, consequently disproving the hypothesis that the problem was due to attenuation alone. There was still, however, significantly poorer performance with plugs than unoccluded. Plugs did not produce significantly more left-right errors, but only front-rear errors, where once again responses favored the rear position. The decrement due to plugs was greater for the white noise than for the tone.

Russell and Noble (1976) further explored these questions by testing the effects of muffs and plugs on the ability to localize white noise from loudspeakers situated at 30 degrees, 60 degrees, 90 degrees, 120 degrees, and 150 degrees azimuths, all on the listener's left side. They examined decision certainty and error magnitude scores, as well as the frontward and rearward error directions. Once again, earmuffs produced a substantially greater

decrement than earplugs. The results for plugs showed slightly (but not significantly) more total errors than in the unoccluded condition, but significantly more rearward errors. Earmuffs resulted in significantly more total errors than in the unoccluded condition, with approximately the same number of rearward errors and significantly more forward errors (in contrast to the earlier finding by Atherly and Noble, 1970). The investigators also found that responses with muffs were considerably more certain in the case of frontward errors. These findings are consistent with a rearward illusion for earplugs and a frontward illusion for earmuffs. The authors believe that they support an information transformation hypothesis for earplugs, suggesting that the effect of plugs is to attenuate high-frequency sounds, in much the same manner as the pinna does with sounds coming from the rear. The result is a rearward illusion. The authors attempt to explain the greater decrements caused by earmuffs by an information reduction theory, in which the important information supplied by the pinna is missing entirely. It is interesting to note that the investigators chose glass-down earplugs, which have relatively poor attenuation in the low frequencies. If their plug had had a flatter spectrum, the "information transformation" might not have occurred at all. In fact, they suggest further research simulating positions in the horizontal plane by varying spectrum levels (Russell and Noble, 1976).

In a subsequent experiment, Noble (1981) tested the effects of earmuffs on both horizontal and vertical localization. By restricting head movements in one condition and allowing free movement of the head and torso in another, he was also able to study the added benefits of exploratory head movement. Ten loudspeakers were placed in the horizontal plane in a range of 180 degrees, and nine were placed vertically in a 160 degree range. Twenty-one subjects, wearing earmuffs and unoccluded, attempted to localize a 1/3-octave band centered at 1000 Hz at a level of 60 dB(A). The signal output was amplified by 25 dB in the occluded condition. Because subjects were to terminate each signal when they had decided on its location, the investigator could measure their response time.

The results showed that earmuffs degraded response accuracy in the horizontal plane and virtually destroyed it in the vertical plane. Free head movement improved the situation considerably, but mainly in the horizontal plane. In the horizontal plane, subjects' response accuracy was 95% in the unoccluded free-head-movement condition, 50% in the occluded free-head-movement condition, and 24% occluded and with the head restricted. Response times were 1.84 second unoccluded, and 6.25 seconds with earmuffs, both in the free-head-movement condition. Results for the vertical plane showed 72% response accuracy in the unoccluded free condition, 19% in the occluded free condition, and nearly random in the restricted-head occluded condition. Response times for the vertical plane were 4.7 seconds in the open-ear free-head-movement condition, and 10.2 seconds in the earmuffs free-head condition.

Noble concludes that the removal of the pinna by earmuffs has a definite adverse effect on horizontal plane localization and a radically disruptive effect on vertical plane localization. These effects are somewhat mitigated by free head movement, but only slightly so in the vertical plane. The investigator noted that subjects moved their heads and torsos considerably, sometimes out of the range of the video camera, and still the responses were only slightly better than chance. According to Noble, earmuff users, even when unrestrained, do not have a good grasp of vertical auditory space. This finding has implications for construction workers or anyone wearing earmuffs in a job requiring vigilance, especially in the up-and-down dimension (Noble, 1981).

Coleman and his colleagues have also noted that hearing protectors can have an adverse effect on the localization of desired sounds (Coleman et al., 1984). They point out that hearing protectors can have detrimental effects on localization in practical situations, and cite Talamo (1982) as showing this problem with tractor drivers. Coleman et al. raise questions as to the practical significance of this problem: i.e. What level of uncertainty is possible before safety and performance are impaired? They suggest that if the ability to localize needs improvement, then plugs are preferable to muffs, or an electronic circumaural earmuff could be developed, which is designed to maintain the sound information as it would be perceived in the unprotected condition (Coleman et al., 1984).

V. SPECIAL PROTECTORS

Over recent decades, certain hearing protectors have been developed with speech communication and signal detection in mind. These protectors may be classified into the categories of passive attenuators, active attenuators, and communication systems. Because the subject of communication systems constitutes an extensive topic on its own, it will not be covered here. It should be sufficient to say that these devices can be extremely useful in protecting hearing and at the same time enhancing speech communication, provided that they possess certain features available with modern technology, such as noise-canceling microphones, wide frequency bandwidths, and fast-acting automatic gain control, as well as adequate noise attenuation.

A. Passive Attenuators

Forshaw and Cruchley (1982) report that Canadian gunners do not like to "don and doff" hearing protectors all the time, but prefer to cover their ears with their hands. Both hands, however, are not always free. For this kind of reason, level dependent or "nonlinear" hearing protectors have been developed that will allow speech communication at moderate intensities, and provide increasing attenuation at high intensities. In the case of earplugs, a small hole in the plug allows frequencies below 1000 Hz to pass with little attenuation (Michael, 1965). At high sound levels the small orifice produces a turbulent flow, increasing impedance especially for high-frequency sounds. Because its greatest effectiveness is for high-frequency, high-level stimuli, this kind of protector was developed specifically for use with impulses from weapons (Mosko and Fletcher, 1971).

The Selectone-K plug, designed by Zwislocki, incorporates a two-stage filter. Figure 7, from Coles and Rice (1966) shows a schematic cross section of the Selectone-K earplug contrasted with the standard V-51R. Another popular design is a modification of the V-51R plug known as the "Gundefender", in which the core of the plug is removed and replaced by a small metal disk containing a hole of 0.0265 inches in diameter (Mosko and Fletcher, 1971). The attenuation of the Gundefender is negligible under about 110 dB, above which it increases, with considerably greater attenuation above 140 dB (Forrest, 1981). Figure 8 (from Forrest, 1971) shows the Gundefender's attenuation growth as a function of peak sound pressure level of 140 dB and above. Measurements were made at the canal entrance and near the tympanic membrane of a cadaver ear.

*Also called the "Gunfender" (see Forshaw and Cruchley, 1982).

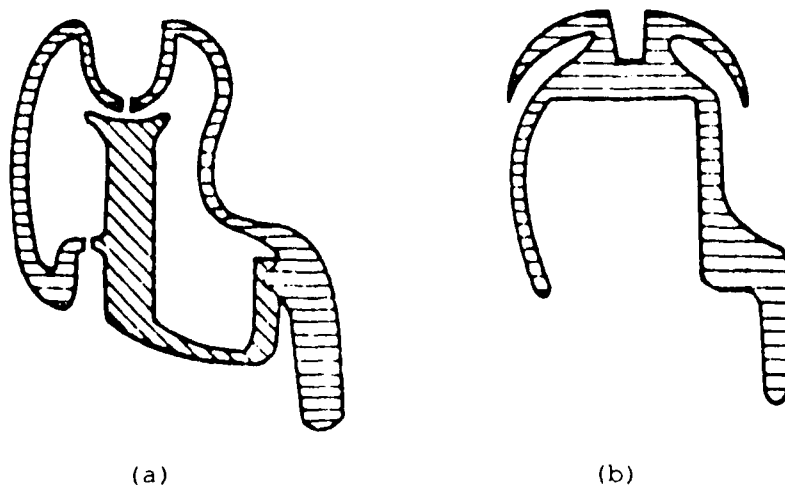


Figure 7. Schematic cross sections of (a) the Selectone-K, and (b) the V-51R earplugs.

Note. From "Letter to the Editor: Earplugs and Impaired Hearing" by R. R. A. Coles and C. G. Rice, 1965, Journal of Sound Vibration, 3, pp. 521-523. Reprinted by permission.

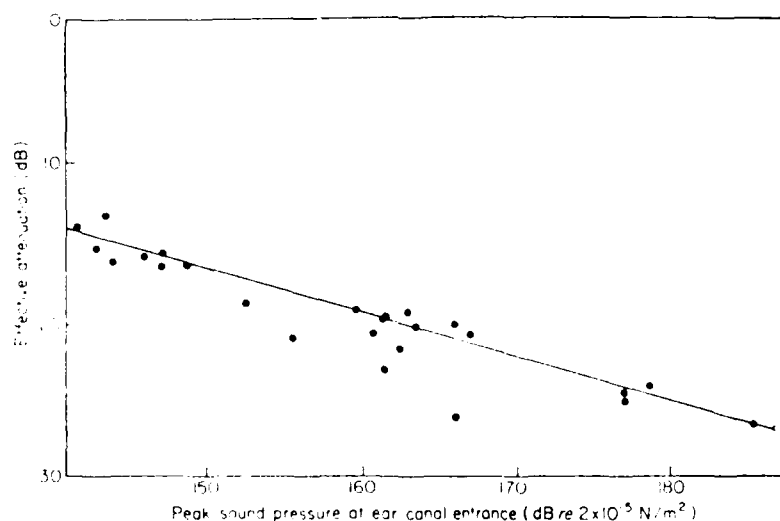


Figure 8. Impulse attenuation from the "Gundefender" earplug as a function of peak SPL at the ear canal entrance.

Note. From "Ear Protection and Hearing in High-Intensity Impulse Noise," by M. R. Forrest, 1971, in D. W. Robinson (Ed.), Occupational Hearing Loss, London: Academic Press.

These types of protectors may present certain problems. Forshaw and Cruchley (1982) warn against using this type of hearing protector in high-level steady-state noise because of its poor low and mid-frequency attenuation. They report that at 850 Hz its attenuation is -8 dB. The orifice also acts as a resonator, and actually amplifies certain frequencies. Michael (1965) states that the metal parts can sometimes injure the ear canal, but he does not give the mechanism for such injuries. Coles and Rice (1966) found that Selectone-K users were dissatisfied with the plugs because they were less comfortable and more difficult to size, fit, and use than the standard V-51R. They also reported that the Selectone-K's central core would sometimes become lost, and that as many as 60% of the plugs fell out during a field experiment involving their use (Coles and Rice, 1966).

There have been some attempts to evaluate the effects of these nonlinear protectors on the intelligibility of speech. Michael (1965) reports substantially higher speech recognition scores for protectors with acoustical filters than for those without filters at speech levels of approximately 45 to 70 dB SPL in a quiet background. In masking noise at 88 dB SPL, performance with the two protectors was much the same for speech levels of 70 to 85 dB SPL. Mosko and Fletcher (1971) found that in moderate noise levels (70 dB SPL) individuals wearing the Gundefender recognized speech better than when using the V-51R, and almost as well as in the unoccluded condition. In high noise levels (100 dB SPL) individuals gave the same scores with the V-51R and in the unoccluded condition, but significantly poorer scores with the Gundefender.

In a laboratory and field investigation of the V-51R and Selectone-K earplugs, Coles and Rice (1966) tested the effects of these protectors on speech recognition in various conditions. In the laboratory, 12 normal-hearing subjects listened to PB monosyllables in three ear conditions (unoccluded, V-51R, and Selectone-K), at sensation levels of 35 and 70 dB, in quiet, and at the 35-dB sensation level at a speech-to-noise ratio of 2 dB. In the field experiment, 12 Royal Marines responded to shouted orders in quiet and with impulse noise (machine gun bursts) in the background at peak sound pressure levels of 156 to 161 dB. Results of the laboratory study indicated that in quiet, the Selectone-K plug necessitates a speech level about 4 dB lower than the V-51R for equivalent intelligibility, although this speech level was about 15 dB higher than that required in the unoccluded condition. In noise, performance with the Selectone-K was not as good as with the V-51R. At optimal listening levels, meaning speech reception threshold plus 35 or plus 70 dB, there was no significant difference in speech recognition scores among the three ear conditions. Results of the field experiment, however, were not quite so satisfactory. In the quiet background, the percentage of orders heard correctly were: 84% unprotected, 73% Selectone-K, and 68% V-51R. Estimated percentage of orders heard correctly in the noise environment were only: 40% unprotected, 34% Selectone-K, and 16% V-51R. Coles and Rice conclude that the Selectone-K allows generally better communication than the V-51R plug, but that it is less comfortable and more difficult to fit and use.

A more recent development in the design of a passive, nonlinear earmuff provides grounds for optimism. Allen and Berger (1987) reported on the design and refinement of a level dependent muff using a valve system to effect low levels of attenuation in low noise levels, with significant amounts of attenuation in impulsive noise conditions. The resulting earmuff is marketed by EAR as the "Ultra 9000". A bank of small orifices in a tuned acoustical duct allow speech and other moderate-level sounds to be heard, but impulses and other high-level sounds above about 120 dB create a turbulent airflow, impeding the passage of these sounds (EAR, 1987). The addition of an

unusually flat attenuation spectrum affords greater speech recognition than is available in most contemporary hearing protectors.

B. Active Attenuators

Two types of earmuffs can be classified as active attenuators. One uses noise cancellation techniques to achieve attenuation. The other uses an amplifier to permit the passage of low and moderate-level sound, maintaining a constant level at the ear. It then acts as a passive attenuator at high levels (Maxwell et al., 1984).

An example of the noise-cancelling system has been described by Jones and Smith (1981). It consists of an open-backed headphone, which produces a sound field at the ear minus the cancelled components, a dual channel cancellation module, and a synchronizing system to the noise source. It provides noise cancellation, especially in the low frequencies, of up to 50 dB, and passive protection in the higher frequencies. Jones and Smith describe their system as light weight and economical, and potentially useful against noise produced by helicopters, air or gas-operated hand tools, vehicle engines, or in engine or control rooms where noise is concentrated in certain frequency regions. They mention that this kind of protector can restore direct speech communication, but they do not elaborate on the speech communication advantages.

Pilots of the experimental aircraft Voyager used another noise cancelling device in their circumnavigation of the globe, allowing them to avoid the permanent hearing loss that their flight surgeon had predicted (Gauger and Sapiejewski, 1987). This system also provides considerable added protection in the low frequencies, producing a relatively flat attenuation which is desirable for speech communication. The system has been jointly developed by the Bose Corporation and the U.S. Air Force, where research on active attenuators continues (McKinley, 1987).

Maxwell and his colleagues describe the effects of the other type of active attenuator on speech recognition in various noise conditions (Maxwell et al., 1987). Landing Signal Officers on aircraft carriers exposed to transient (1-2 second) noise levels at 120 dB(A) have expressed reluctance to wear hearing protection because of the need to communicate with pilots through a telephone handset. Consequently, the authors evaluated four active attenuation devices for certain physical parameters, and two of the four for speech intelligibility. Using the Tri-Word Modified Rhyme Test in four levels of Gaussian noise and at two speech-to-noise ratios, they found that in the more favorable speech-to-noise ratio (+4 dB), speech recognition was always better in the unprotected condition, but that one device produced scores that were nearly as good in the highest noise level (90 dB SPL). In the more difficult speech-to-noise ratio (0 dB) the same device produced better speech recognition scores than the unprotected condition in the lowest (60 dB) and highest (90 dB) noise levels, but not in the intermediate noise levels. Individuals wearing the other device performed consistently more poorly than in the unoccluded condition, particularly in the higher noise levels. Maxwell et al. also found that although attenuation in the passive mode was generally good (about 32-35 dB), two of the three commercially available devices fell considerably short of the manufacturer's specifications, and of the authors' stated criteria for these kinds of protectors. The level at which the devices stopped amplifying and acted as passive protectors was considerably lower than it should have been, and there were no plateaus produced by selective amplification at levels around 85 dB. One of the commercially available

devices, as well as the Navy's own prototype, came quite close to the target criteria, but these two devices were not tested for speech intelligibility. These results suggest that this type of active hearing protector can be of some benefit to speech communication, but that these protectors need to be evaluated further before they are used in situations where speech communication is critical.

VI. SUMMARY

Many industrial workers and soldiers dislike wearing hearing protectors, claiming that they interfere with communication and the perception of warning signals. Theoretically, hearing protectors should actually improve communication in high noise levels. While this is often the case, both laboratory and field research points to numerous conditions where protectors provide no improvement, or have an adverse effect.

Effects on Speech Communication

Hearing protectors attenuate the noise and the signal by equal amounts within a given frequency range, reducing both to a level where there is less distortion, and providing better listening conditions. These improvements can be experienced when the noise level is above 80 to 90 dB, the listener has normal hearing, and the talker is not wearing protectors. Even when these conditions are met, the crossover level from disadvantage to advantage can be somewhat higher (for example, over 100 dB), depending on speech-to-noise ratio.

Hearing protectors usually have an adverse effect on speech recognition when the listener is hearing impaired. This appears to be true of listeners with average hearing threshold levels greater than 30 dB at 2000, 3000, and 4000 Hz. The most plausible mechanism for this occurrence is the reduction of certain signals below the level of audibility, eliminating important speech cues, particularly those in the high frequencies.

In addition to hearing loss, other conditions interact with hearing protectors to affect speech recognition. Visual cues aid speech recognition, with and without protection, and may even decrease any disadvantages due to the wearing of protectors. The talker's ear condition also affects the listener's ability to understand speech. Due to the "Occlusion Effect", the talker's voice sounds louder, and hence the vocal output is 2 to 4 dB lower. The result is a decrease in speech recognition by the listener, which more than offsets any gains that would have occurred from the use of protectors, had only the listener worn them. Talkers with hearing protectors also appear to articulate more rapidly and pause more briefly between words. The poorest performance occurs when both talkers and listeners wear hearing protectors, which most closely resembles real-life conditions. This situation can be mitigated somewhat through verbal feedback. It also seems that earmuffs have a greater adverse effect on speech recognition than earplugs, although this difference may be due to the spectral properties of the devices tested rather than any other physical characteristics peculiar to earmuffs.

Effects on Warning Signals

The same kinds of theoretical considerations that apply to speech recognition hold for the detection of warning signals while wearing hearing protection. The attenuation of high noise and signal levels facilitates the perception of signals by taking them out of the range of distortion. This is generally borne out by the research, using normal-hearing listeners, relatively high noise and signal levels, and simple detection paradigms. The crossover level between disadvantage and advantage of hearing protectors appears to be about the same as it is for speech recognition: about 80 to 90 dB.

Hearing protection can degrade the ability to detect warning sounds under various conditions. Protectors are more likely to be responsible for adverse effects when the signal is unexpected, and especially when it is embedded among other similar but irrelevant stimuli. Not unexpectedly, hearing protection appears to degrade signal detection by individuals with impaired hearing, although the research in this area is not as extensive as in the area of speech recognition. The only industrial field study (Wilkins, 1984) is plagued by methodological problems, but it does tend to support the laboratory results, in that subjects wearing hearing protectors (most of whom had some degree of noise-induced hearing loss) gave fewer correct responses to a difficult-to-recognize target sound, than when they listened in the unprotected mode.

Once again, research has indicated that earmuffs cause a greater decrement than earplugs. One study found a consistent enhancement of signal detection by plugs, but a consistently adverse effect on the part of muffs (Lazarus et al., 1983b).

That both plugs and muffs adversely affect the ability to localize acoustic signals is quite clear, and this is especially true of muffs. Earplugs produce mainly ipsilateral (front-back) effects, with significantly more rearward errors, indicating a rearward illusion of the sound source. Earmuffs are the cause of contralateral (left-right) localization errors, as well as ipsilateral errors, with an apparent tendency toward a frontward illusion of the sound source. Earmuffs drastically impede localization in the vertical plane, even with free head movement.

These findings have serious implications for safety in noisy working conditions. Warning signals not only need to be detected and recognized, but their locations must be determined, so that individuals may either approach and remedy the situation or get out of the way.

Special Protectors

Various kinds of special protectors have been developed to enhance speech communication during noise exposure and to permit it during quiet intervals.

Special passive attenuators can improve communication with protectors during the quiet intervals between noise bursts, so that the wearers are not compelled to take them on and off so frequently. Passive attenuators include modifications of the V-51R plug, such as the Selectone-K and the Gundefender, and a new nonlinear earmuff, the EAR Ultra 9000. These protectors give very little attenuation at moderate noise levels (even acting as amplifiers at times), but increasingly greater attenuation at levels over about 110 to 120

dB. Because of this they are mainly useful in impulsive noise conditions, such as firing ranges. Speech recognition experiments with nonlinear plugs indicate that they can enhance performance in moderate speech levels (around 70 to 88 dB), and above these levels produce about the same speech recognition as a standard earplug. It appears, however, that the comfort and practicality of these devices leaves something to be desired. These problems may not apply to the nonlinear muffs.

Through the use of modern technology, special protectors also can enhance communication in certain noisy conditions, and permit communication in levels of noise where it would otherwise be impossible. These protectors employ active attenuation techniques. One type uses noise cancellation mechanisms. The other uses an amplifier, which maintains a constant signal level at the ear, cutting off at levels above 85 to 90 dB where the device acts as a passive attenuator. Speech intelligibility testing with the amplifying protector indicates performance advantages under some conditions, but not others. Physical measurements indicate that these products do not always conform to the manufacturer's specifications, so benefits to speech communication cannot necessarily be assumed. It appears that both types of device are still in the developmental stage.

VII. RESEARCH RECOMMENDATIONS

1. Because of the adverse effect of hearing protector attenuation that slopes toward the high frequencies, especially with hearing-impaired users, attempts should be made to develop and test devices with relatively flat attenuation spectra. These devices should be tested not only for speech recognition, but for possible improvements in signal detection and localization, with normal-hearing and hearing-impaired subjects. If the anticipated improvements are realized, this type of effort could stimulate the development and standardization of a mechanism for rating hearing protection with respect to speech communication and signal detection effects.

2. The apparent differences between the effects of plugs and muffs on speech communication and signal perception need to be explored further. If such differences systematically occur, we need to know whether they are due to spectral differences or to some other factor.

3. Well designed and controlled research needs to be conducted on the effects of hearing protection on the perception of warning signals and machinery malfunction in sufficiently large populations of listeners with a range of hearing impairments. They should include warning signals and other target sounds that are representative of the military environment.

4. The effects of earplugs on localization in the vertical plane need to be investigated.

5. The development of a more practical, wearable, nonlinear earplug should be encouraged.

6. Speech and signal perception with active attenuators need to be studied more extensively. There should be further testing of the physical properties of these devices, and efforts to encourage quality control on the part of the manufacturers.

7. Finally, it would be useful to know more precisely the extent of user dissatisfaction due to speech communication and signal perception difficulties, as opposed to other factors, such as comfort and appearance, and under what conditions these difficulties occur. This kind of information could be gained through the use of carefully worded, anonymous surveys.

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